

A new approach to anti-neutrino running in long baseline neutrino oscillation experiments

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We study the possibility to replace the anti-neutrino run of a long baseline neutrino oscillation experiment, with anti-neutrinos from muon decay at rest. The low energy of these neutrinos allows the use of inverse beta decay for detection in a Gadolinium-doped water Cerenkov detector. We show that this approach yields a factor of five times larger anti-neutrino event sample. The resulting discovery reaches in θ_{13} , the mass hierarchy and leptonic CP violation are compared with those from a conventional superbeam experiment with combined neutrino and anti-neutrino running. We find that this approach yields a greatly improved reach for CP violation and θ_{13} while leaving the ability to measure the mass hierarchy intact.

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The fact that our Universe is made out of matter and not anti-matter constitutes one of the great open questions in physics. The conditions required to obtain a baryon asymmetry from a CP symmetric initial state were identified by Sakharov more than 50 years ago [1]. They are deviation from thermal equilibrium, baryon number violation and CP violation. Of these three ingredients, CP violation has proven to be the most elusive. While some small amount of CP violation exists in quark mixing [2, 3], it is not sufficient to explain the baryon asymmetry of the Universe [4]. Therefore, the quest for new sources of CP violation continues to be a guiding theme for much of particle physics. Leptonic CP violation has been proposed as a mechanism to explain the baryon asymmetry of the Universe, so called leptogenesis [5], and with the discovery of neutrino oscillation [6] leptogenesis has become a very plausible scenario. The discovery of CP violation in the lepton sector would constitute a smoking gun for this mechanism. In addition the mere existence of neutrino oscillations implies a neutrino mixing matrix in the same fashion as the CKM matrix in the quark sector, and with three generations there will be at least one CP phase.

Studying CP violation in neutrino oscillation, requires the use of appearance channels, when the neutrino changes flavor from production to detection. Since ν_τ are very hard to detect and to produce, naturally, all proposed methods focus on using transitions between $\nu_e \leftrightarrow \nu_\mu$ and $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$. There are various proposals for novel techniques to produce neutrino and anti-neutrino beams, either from the decays of muons (neutrino factories), or from the β -decay of short-lived, artificially produced radioactive nuclei (β -beams), see *e.g.* [7]. While these concepts may ultimately provide the best sensitivity to CP violation, in the near term conventional neutrino and anti-neutrino beams based on the decay of horn focused pions are the option of choice (superbeams). All beam based approaches to neutrino oscillation are performed with neutrinos in the energy range from a few

hundred to many thousand MeV. In this energy range charged current reactions provide the dominant detection mechanism. At the atmospheric mass squared difference these energies imply a source detector distance from 100 km up to several 1,000 km, hence these experiments are known as long baseline experiments.

In the context of superbeam experiments, a CP violation measurement requires data from both $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. However, the anti-neutrino run poses a number of specific challenges: the production rate for π^- , the parent of $\bar{\nu}_\mu$, is lower than for π^+ , the anti-neutrino charged current cross section is lower, the background levels are higher¹, and the systematic errors are expected to be larger. Overall, the event rate for anti-neutrinos is suppressed by a factor of 2-5, depending on the anti-neutrino energy, which is illustrated by table I.

On the other hand, for energies below about 100 MeV the situation is quite the opposite, strongly favoring the use of anti-neutrinos. In this energy range the dominant process is inverse β -decay, (IBD), $\bar{\nu}_e + p \rightarrow e^+ + n$. This process provides a very useful delayed coincidence tag between the prompt positron and the delayed neutron capture, which is the reason why this reaction was used by Reines and Cowan to discover the neutrino [8]. At these energies copious sources of anti-neutrinos exist. In this letter we focus on $\bar{\nu}_\mu$ from μ^+ decay at rest from a stopped pion beam.

In a stopped pion source a proton beam of a few GeV energy interacts in a target producing both π^+ and π^- . The pions then are brought to rest in a high-Z beam stop. The π^- , and also the daughter μ^- , will capture on the high-Z nuclei. The π^+ will produce the following cascade

¹ This is due to the larger contamination from wrong sign pions.

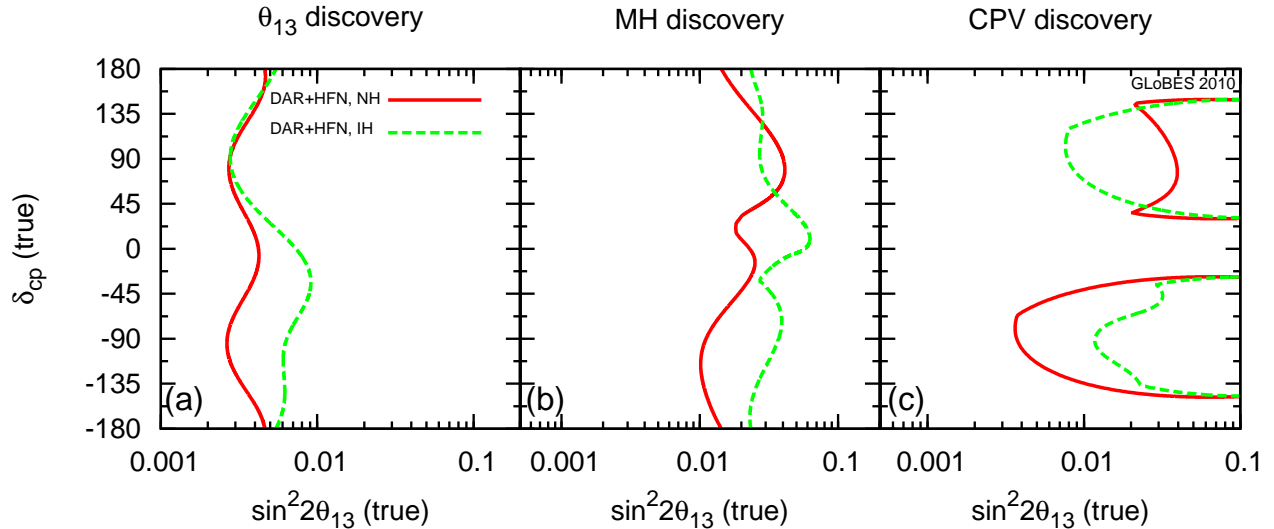


FIG. 1: Discovery reaches at 3σ confidence level from left to right for θ_{13} , mass hierarchy and CP violation for 6 years of DAR+HFN for normal (NH) and inverted (IH) true mass hierarchy.

of decays

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \nu_\mu \\ &\quad \downarrow \\ &\quad e^+ + \nu_e + \bar{\nu}_\mu \end{aligned}$$

resulting in ν_μ , $\bar{\nu}_\mu$ and ν_e , but no $\bar{\nu}_e$. The $\bar{\nu}_\mu$ can oscillate into a $\bar{\nu}_e$ and this $\bar{\nu}_e$ can be detected and uniquely identified by IBD. This concept has been used for instance in the LSND experiment [9]. We will denote this combination of anti-neutrino source and IBD detection as muon decay at rest (DAR).

The central idea of this letter is to combine a horn focused high energy ν_μ beam, henceforth denoted as horn focused neutrino beam (HFN) with $\bar{\nu}_\mu$ from a DAR setup to study θ_{13} , the mass hierarchy and leptonic CP violation. This is in contrast to reference [10], where an entirely DAR based experiment was considered to measure leptonic CP violation. In a pure DAR setup there is no information on the mass hierarchy and therefore a CP measurement is only feasible assuming that the mass hierarchy has been determined by other means. We show that the combination of HFN and DAR allows one to address both the mass hierarchy and CP violation at the same time. Throughout this letter, we will denote this new technique as DAR+HFN.

To illustrate the strength of DAR+HFN, we will study a specific setup, which closely resembles the Fermilab DUSEL concept for a long baseline experiment, currently known as LBNE. Obviously, similar considerations hold for any superbeam experiment. This setup has a total running time of 6 years and a 100 kt water Cerenkov detector. The entire HFN part is very similar to the setup described in detail in [11], specifically we take the source detector distance to be 1300 km and use the same detec-

tor performance. The beam delivers 6.2×10^{20} protons on target per year, which for 120 GeV protons corresponds roughly to 700 kW of beam power.

The feasibility of a high intensity DAR source hinges on the availability of cost effective, megawatt proton accelerators in the GeV range. We use the same proton source parameters as in reference [10] which are 4×10^{22} of ν_e , ν_μ and $\bar{\nu}_\mu$ per flavor per year per accelerator. We use 4 of these accelerators with a source detector distance of 20 km. We determined this distance to be the optimal baseline for our purposes, by performing a scan of baselines in 1 km increments from 4 – 24 km. We also tested that putting all sources at the same distance provides the best performance. In order to allow for an efficient detection of the IBD signal, the water Cerenkov detector will need to be doped with Gadolinium (Gd) [12]. Gadolinium-doping decreases the neutron capture time and improves the neutron capture signature. Recent experimental tests of this concept [13] indicate a detection efficiency of 67%, which we will use for our calculation. Due to the strong π^- absorption in the target, the $\bar{\nu}_e$ contamination is very small $\sim 4 \times 10^{-4}$, but fully taken into account [9]. The non-beam backgrounds, which mostly stem from atmospheric neutrino interactions are taken from reference [10] and scaled to a 6 year run with a 100 kt detector. The energy resolution for IBD events is identical to the one for positrons and is parametrized as $\sigma(E) = 5\% \sqrt{E/\text{GeV}}$ [14].

The very different duty factors, d , of the HFN source, $d < 10^{-4}$, and DAR source, $d \simeq 0.1$, allow for concurrent operation. As shown in table I, the event numbers from both sources are comparable and thus the probability of finding events from both source happening at the same

time is approximately given by the ratio of their duty factors, which is 0.001. This is equivalent to less than 0.5 events for the duration of the experiment. Obviously, for a superbeam it is not possible to run neutrinos and anti-neutrinos simultaneously, since the horn² either focuses π^+ or π^- .

Note, that the disparate baselines reflect the different neutrino and anti-neutrino energies and the ratio of baseline to energy (L/E) is nearly the same for HFN and DAR. For comparison we also present results for a pure superbeam experiment of the same total duration, target mass and number of protons on target per year, which consists of 3 years of HFN operation followed by 3 years of horn focused anti-neutrino (HFA) operation. The performance for both periods is taken from reference [11]. This setup is denoted by HFA+HFN.

In table I, we compare the total event rates for the 6 year DAR+HFN and HFA+HFN runs. For the oscillation parameters chosen, DAR+HFN has twice the statistics in the neutrino mode and five times as much statistics with a five times better signal to background ratio in the anti-neutrino mode.

	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	bgn	$\nu_\mu \rightarrow \nu_e$	bgn
DAR+HFN	398	73	511	143
HFA+HFN	77	53	255	71

TABLE I: Comparison of the signal and background event rates of 6 years running of DAR+HFN and HFA+HFN. Note, that for DAR+HFN this is 6 years of simultaneous running of neutrino and anti-neutrinos, whereas for HFA+HFN this is 3 years each, run consecutively. Oscillation parameters are $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$ and normal hierarchy.

For our statistical analysis we use the techniques outlined in [15]. We bin our DAR data into bins of 1 MeV and the HFN/HFA data into bins of 125 MeV. We include a 5% systematic on the total number of signal events and a (uncorrelated) 5% systematic on the total number of background events. All physics sensitivities have been computed using GLoBES [16] and are shown at 3σ confidence level. The oscillation parameters are $\sin^2 \theta_{12} = 0.3$, $\sin^2 \theta_{23} = 0.5$, $\Delta m_{31}^2 = 2.4 \times 10^{-3} \text{ eV}^2$, $\Delta m_{21}^2 = 7.9 \times 10^{-5} \text{ eV}^2$ and we include a 10% error on the atmospheric parameters, a 5% error on the solar parameters and a 2% matter density uncertainty. In the fit the mass hierarchy is free.

In figure 1 we show the resulting discovery reaches for θ_{13} , the mass hierarchy and CP violation for DAR+HFN as a function of the true values of $\sin^2 2\theta_{13}$ and δ_{CP} for both

the normal and inverted true hierarchy as labeled in the legend. Due to the asymmetric nature of this experiment and the fact that matter effects are relevant only for the HFN run, there is a pronounced effect from changing the input (true) mass hierarchy. However, in both cases the synergy between the HFN and DAR is apparent.

In figure 2, we compare the results from DAR+HFN with HFA+HFN. The reaches are given as a fraction of δ_{CP} and as a function of the true value of $\sin^2 2\theta_{13}$. In panel (a), we show the results for the discovery of the θ_{13} and find that DAR+HFN outperforms the superbeam experiment HFA+HFN for all CP phases and both hierarchies by roughly a factor two. The discovery reach for the mass hierarchy is shown in panel (b) and here, we see that for some values of the CP phase, in particular for inverted mass hierarchy, the reach is somewhat smaller for DAR+HFN. If at the end of the DAR+HFN run, the mass hierarchy has not been discovered adding a HFA run may be required. Finally, in panel (c) the discovery reach for CP violation is shown. DAR+HFN improves the reach for small θ_{13} by a factor between 3 and 10 depending on the mass hierarchy and by about 75% for large θ_{13} .

Summarizing, we have demonstrated that a combination of low energy $\bar{\nu}_\mu$ from muon decay at rest with high energy ν_μ from a superbeam aimed at the same Gadolinium-doped water Cerenkov detector yields a moderately improved reach for θ_{13} and a vastly improved discovery reach for CP violation while only marginally affecting the mass hierarchy sensitivity. These improvements are a direct result of combining an optimized neutrino with an optimized anti-neutrino run. The practicality of this proposal, however, depends critically on the feasibility of low-cost, high-intensity stopped pion sources.

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² With a solenoid it is possible to focus both types of pions, but that leaves the problem of lepton charge identification in the detector.

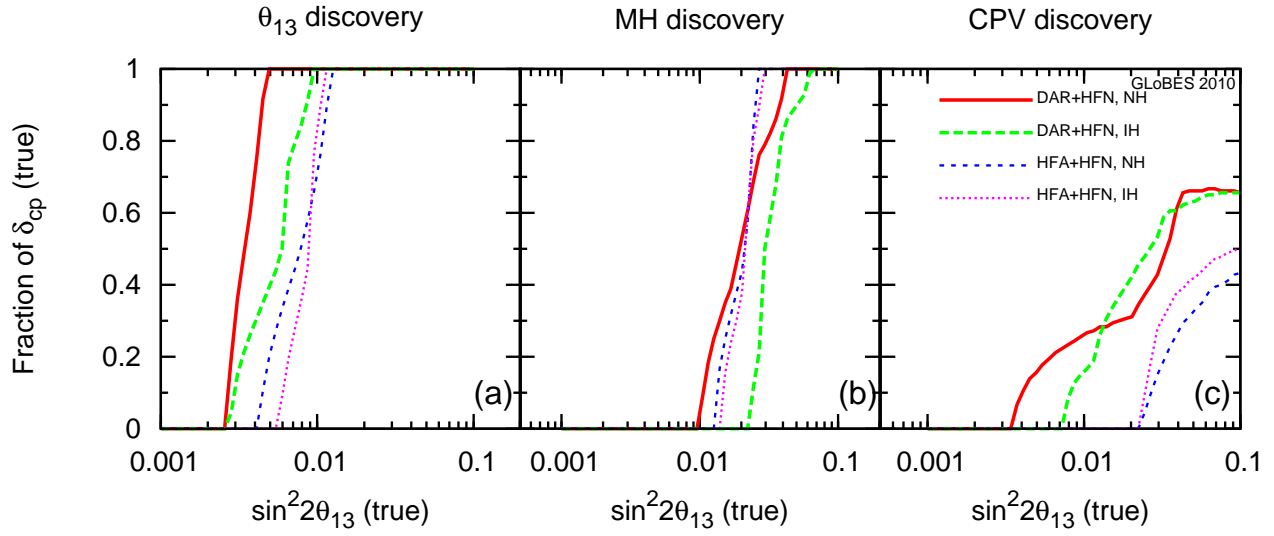


FIG. 2: CP fractions for which a discovery at 3σ confidence level is possible as function of $\sin^2 2\theta_{13}$. From left to right for θ_{13} , mass hierarchy and CP violation. The different lines are for normal (NH) and inverted (IH) true mass hierarchies and for DAR+HFN and HFA+HFN, respectively.

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